

TOTAL TEMPERATURE MEASUREMENTS IN A SHOCK TUNNEL FACILITY

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ABSTRACT

A fast-response total temperature probe relying on transient heat flux measurements at different surface temperatures has been developed. The technique has been used previously in relatively low temperature facilities using thin film gauges, but has now been extended using rubbed junction thermocouple gauges in order to access higher flow total temperatures and more abrasive flow conditions. Construction, calibration, and operation of the probe are discussed. The utility of the probe is demonstrated through measurements of the time-resolved total temperature variations within a small shock tunnel facility.

INTRODUCTION

Total temperature measurements are needed in a wide variety of compressible flows in order to accurately define free stream flow conditions, and assess variations associated with work, heat transfer, and viscous effects.

Transient heat flux measurements at the stagnation point of a probe can be used to deduce the flow total temperature provided a suitable correlation for the convective heat transfer coefficient is available. Such techniques have been used with some success in intermittent and impulse facilities (Edney, 1967; Olivier, 1993). However, the need for a heat transfer coefficient correlation can introduce a large degree of uncertainty, particularly when there is turbulence or unsteadiness, or when flow composition variations accompany the temperature changes.

To avoid the need for a heat transfer coefficient correlation, while retaining the relatively robust and high bandwidth characteristics of transient heat flux probes, a technique which relies on the operation of two gauges at different temperatures was developed (Buttsworth and Jones, 1996). The probe, which utilised platinum thin film gauges, has been demonstrated in a variety of wind tunnel facilities in which the flow total temperature was generally less than 800 K (e.g. Buttsworth et al., 1997).

For accurate measurements in more abrasive flows having higher total temperatures, an even more robust transient heat flux gauge, the rubbed junction thermocouple, can be used. The current work describes the development of the gauge which can operate at high

surface temperatures. The utility of the new device is demonstrated through total temperature measurements within a small shock tunnel facility.

TOTAL TEMPERATURE PROBE

Operating Principles

The transient heat flux, q registered by a gauge can be determined from the measured surface temperature history using

$$q = \frac{\sqrt{\rho c k}}{\sqrt{\pi}} \int_0^t \frac{dT/d\tau}{(t-\tau)^{1/2}} d\tau \quad (1)$$

(assuming semi-infinite flat plate operation, e.g., Schultz and Jones, 1973). The stagnation point heat flux is driven by the temperature difference across the boundary layer and can be written,

$$q = h(T_t - T_w) \quad (2)$$

where h is the convective heat transfer coefficient, T_t is the flow total temperature, and T_w is the temperature at the surface of the gauge. As h is only a weak function of the flow and surface temperatures, it can be treated as a constant to within the accuracy of the heat flux measurements. If we operate at two different surface temperatures (indicated by subscripts 1 and 2), two different heat fluxes will be measured, and the flow total temperature can be determined using,

$$T_t = \frac{q_2 T_{w1} - q_1 T_{w2}}{q_2 - q_1} \quad (3)$$

If additional gauges are used, or if multiple experiments are performed at different probe surface temperatures, then the flow total temperature can be determined from a linear regression to the heat flux versus probe temperature data.

Construction

Rubbed junction thermocouple gauges used in shock tunnel facilities are usually of a coaxial construction with an epoxy for insulating and bonding the two dissimilar metals (e.g., Gai and Joe, 1992). The low thermal inertia

junction is usually formed by dragging thermocouple material across the insulation with abrasive paper. This general construction is followed in the present work Fig. 1, with the exception that the insulating and bonding is achieved by building up a layer of oxidation on the K-type thermocouple components (around 6 hours in a furnace at 1000 °C). The insulating material between the chromel and alumel is around 20 μm thick. An example of junctions formed with the present construction technique is presented in Fig. 2.

To heat the gauge, a DC current is passed through a nichrome resistance heating wire wound directly onto the coaxial thermocouple as shown in Fig. 1. It is generally necessary to switch off the heating current prior to a run in order to reduce the noise on the thermocouple.

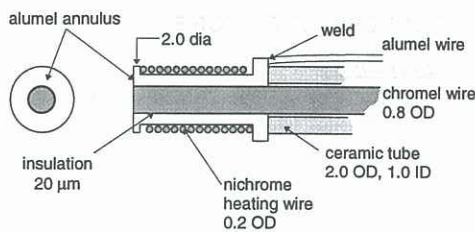


Figure 1: Illustration of the gauge construction. (Dimensions in mm unless noted otherwise.)

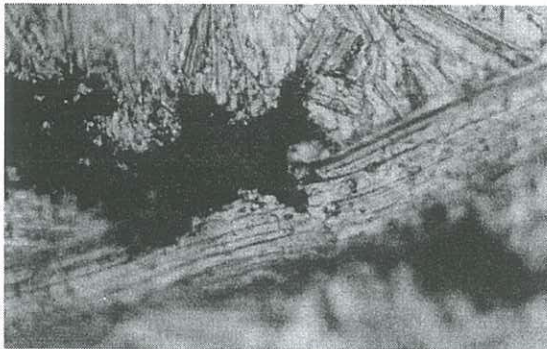


Figure 2: Photograph of a junction between the chromel and alumel materials. (The image corresponds to an area 121 μm wide by 76 μm high.)

Calibration

For accurate heat flux measurements it is necessary to know the value of the thermal product, $(\rho ck)^{1/2}$ for the transient thermocouple gauge (see Eq. 1). Thermal properties data for chromel and alumel materials are presented in Fig. 3 and Fig. 4. This data was obtained from Caldwell (1962) and Touloukian (1970) with $\rho_{\text{chromel}} = 8730 \text{ kg.m}^{-3}$ and $\rho_{\text{alumel}} = 8600 \text{ kg.m}^{-3}$.

For other rubbed junction thermocouple gauges, a hot water bath plunging technique has been used to

determine the value of $(\rho ck)^{1/2}$ at close to room temperature (Jessen et al., 1993). Similar experiments have been performed with the present gauges by dropping room temperature water onto the preheated gauges. A value close to $10\,000 \text{ J.m}^{-2}.\text{K}^{-1}.\text{s}^{-0.5}$ was obtained from these experiments. This is in close agreement with the mean value for the chromel and alumel material at room temperature (see Fig. 4).

However, as the thermal products for the chromel and alumel materials differ from the mean value by around 15 % at room temperature, water calibrations may not indicate the most appropriate value of $(\rho ck)^{1/2}$ for use in the actual experiments. The influence of the uncertainty in $(\rho ck)^{1/2}$ on the total temperature measurement can be reduced by operating the transient heat flux gauge very close to the flow total temperature. In the case of gauge operation at precisely the flow total temperature, no heat flux will be registered regardless of the value of $(\rho ck)^{1/2}$.

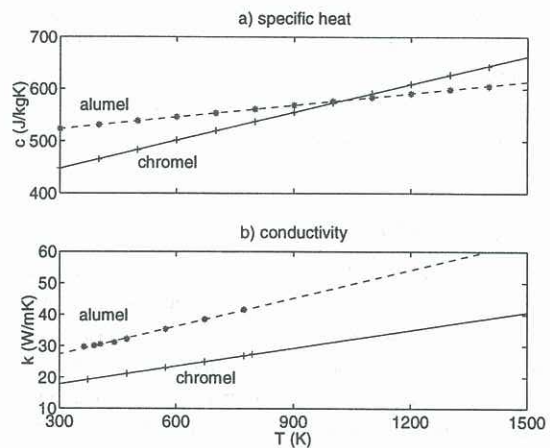


Figure 3: Specific heat and conductivity for chromel and alumel materials from Caldwell (1962) and Touloukian (1970).

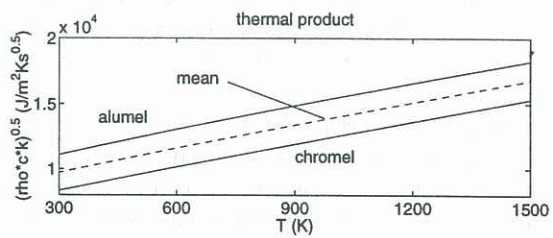


Figure 4: Thermal product, $(\rho ck)^{1/2}$ for chromel and alumel materials.

SHOCK TUNNEL EXPERIMENTS

Experimental Results

Experiments were performed in a small shock tunnel facility in the Department of Mechanical Engineering at The University of Queensland (Austin et al., 1997) as

illustrated in Fig. 5. Prior to a run, the facility was evacuated to around 3 torr. The driver was then filled with nitrogen to 3.25 MPa, and the shock tube was filled with nitrogen to 30 kPa. The primary diaphragm was ruptured mechanically.

Data obtained during four different runs was used to determine the flow total temperature. The nozzle reservoir pressure and pitot pressure histories measured at the locations indicated in Fig. 5 and averaged over the four runs are presented in Fig. 6. Over the four runs the shock speed between the thin film gauge and the nozzle reservoir pressure transducer was $815 \pm 15 \text{ m.s}^{-1}$, and the pitot pressure in the steady region (between approximately 1 and 2 ms on the scale in Fig. 6b was $94.5 \pm 1.5 \text{ kPa}$. The average ambient temperature during this series of experiments was 22.5°C .

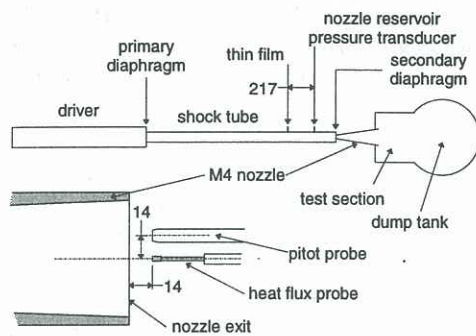


Figure 5: Configuration of the shock tunnel and probes. (Dimensions in mm.)

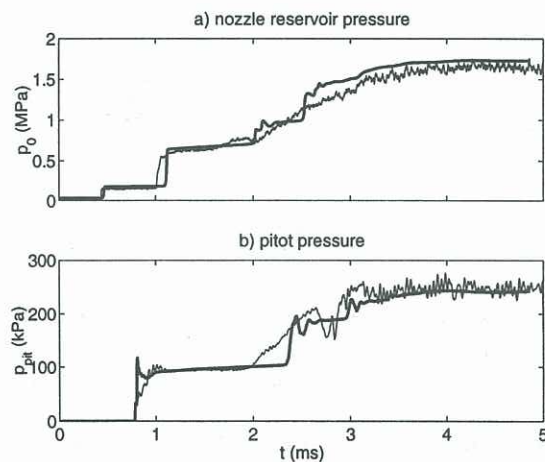


Figure 6: Nozzle reservoir and pitot pressure measurement (light lines) with numerical simulations (heavy lines).

For each shock tunnel run, the heat flux probe was preheated to a different temperature. Figure 7 presents the transient surface temperature measurements and the corresponding heat flux measurements obtained from a numerical implementation of Eq. 1 for each of the four runs. At each point in time, a linear regression for the

heat flux versus probe temperature data was used to determine the flow total temperature. (The value of probe temperature where the regression indicates a zero heat flux corresponds to the flow total temperature). The flow total temperature measurements obtained using this procedure are presented in Fig. 8.

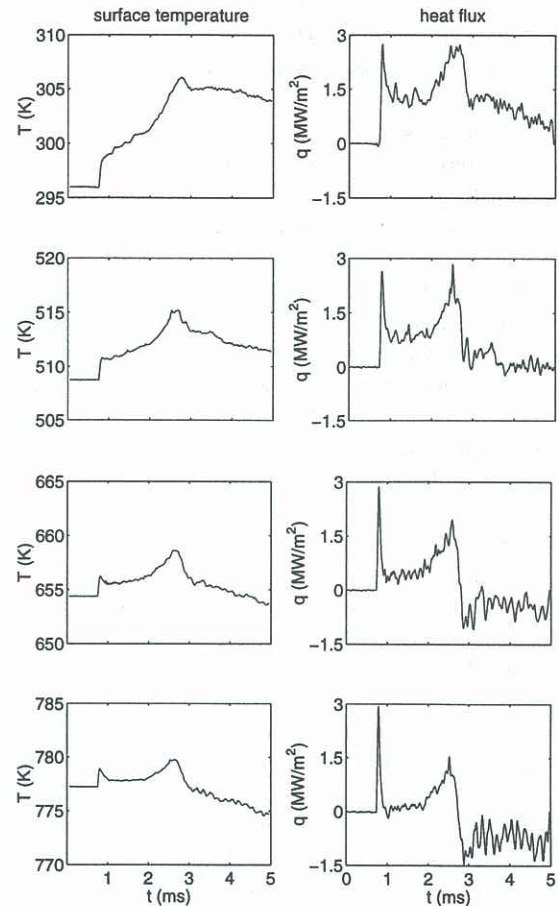


Figure 7 : Probe surface temperature and heat flux measurements.

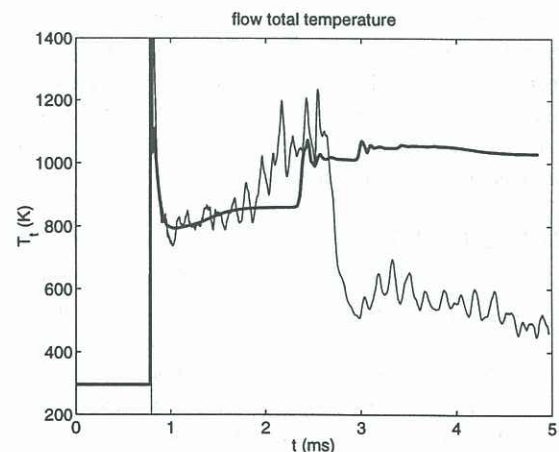


Figure 8: Flow total temperature measurement (light line) and numerical simulation (heavy line).

Numerical Simulations

A simulation of the entire shock tunnel operation was performed using a quasi-one-dimensional formulation which models the area variation with distance along the shock tunnel (Jacobs, 1994). Results from this simulation are presented in Figs. 6 and 8 for comparison with the experimental measurements. The simulated shock speed between the thin film and nozzle reservoir pressure transducer was 793 m.s^{-1} which is within 3 % of the average value measured over the four shock tunnel runs.

Within the steady flow region (1 to 2 ms on the scale in Fig. 6b) there is good agreement between the simulated pitot pressure and the experimental measurements. The total temperature measurements are also in good agreement with the numerical simulations for the first millisecond of the shock tunnel flow (Fig. 8).

The present operating condition is over tailored meaning that the shock wave which is reflected from the end of the shock tube reflects again from the driver gas-test gas interface as a shock wave. In the simulations, the effects of the additional compression due to over tailoring appear as a shock wave at about 2.4 ms on the scale in Fig. 6b and Fig. 8, whereas experimentally, the effects of the compression are smeared over the period between approximately 2 ms and 2.5 ms. The smeared compression effect is associated with the diffuse nature of the driver gas-test gas interface due to turbulent mixing. The interface mixing is not modelled in the quasi-one-dimensional simulations.

From the total temperature measurements (Fig. 8) it appears that the relatively cold driver gas begins to arrive in the test section at approximately 2.5 ms on the scale in Fig. 8. This is significantly earlier than suggested by the simulations which indicate the interface hasn't passed into the test section even after 4 ms of flow drainage. The arrival time of the colder driver gas is not expected to be captured by the quasi-one-dimensional simulation due to two modelling deficiencies. (i) The present simulation does not include Mirel's mechanism for losing test gas to the boundary layer on the shock tube wall, thus shortening the nominal test gas slug and (ii) no mixing is permitted at the driver-gas test-gas interface. As mentioned previously, this second limitation maintains an unrealistically sharp interface, and it also eliminates the important mechanism of driver-gas jetting that is initiated with the passage of the reflected shock.

CONCLUSIONS

The present work represents a successful demonstration of the total temperature probe technique using rubbed junction gauges. To accurately measure total temperatures higher than the maximum operating temperature of the thermocouple (which is theoretically around 1500 K for the K-type material used here), it will be necessary to ascertain the true thermal product of the gauge, particularly at elevated surface temperatures.

The numerical simulations gave an accurate indication of the initial flow conditions, including the total temperature. As expected, the numerical calculations did not accurately predict the details of the compression associated with the over tailored shock tunnel condition, nor the arrival time of the driver gas due to the absence of suitable entrainment and mixing models and the quasi-one-dimensional nature of the simulations.

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